

TAUP 2869/07  
 WIS/03/08-FEB-DPP  
 ANL-HEP-PR-08-7

## Possibility of Exotic States in the Upsilon system

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### Abstract

Recent data from Belle show unusually large partial widths  $\Upsilon(5S) \rightarrow \Upsilon(1S) \pi^+ \pi^-$  and  $\Upsilon(5S) \rightarrow \Upsilon(2S) \pi^+ \pi^-$ . The  $Z(4430)$  narrow resonance also reported by Belle in  $\psi' \pi^+$  spectrum has the properties expected of a  $\bar{c} c u \bar{d}$  charged isovector tetraquark  $T_{cc}^\pm$ . The analogous state  $T_{bb}^\pm$  in the bottom sector might mediate anomalously large cascade decays in the Upsilon system,  $\Upsilon(mS) \rightarrow T_{bb}^\pm \pi^\mp \rightarrow \Upsilon(nS) \pi^+ \pi^-$ , with a tetraquark-pion intermediate state. We suggest looking for the  $\bar{b} b u \bar{d}$  tetraquark in these decays as peaks in the invariant mass of  $\Upsilon(1S) \pi$  or  $\Upsilon(2S) \pi$  systems. The  $\bar{b} b u \bar{s}$  tetraquark can appear in the observed decays  $\Upsilon(5S) \rightarrow \Upsilon(1S) K^+ K^-$  as a peak in the invariant mass of  $\Upsilon(1S) K$  system. We review the model showing that these tetraquarks are below the two heavy meson threshold, but respectively above the  $\Upsilon \pi \pi$  and  $\Upsilon K \bar{K}$  thresholds.

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## I. INTRODUCTION

Conclusive evidence for the first unambiguously multi-quark states would be obtained by finding isovector states or strange states containing heavy quark pairs. The presence of possible tetraquark states containing heavy quarks has been extensively discussed. Simple calculations [1] indicate that such tetraquarks containing heavy quark-antiquark pairs might be observed as pion-charmonium or pion-bottomonium resonances. Such resonances have been observed above the threshold for decays into two heavy mesons. For the bottomonium system our calculations predict tetraquarks with masses below the threshold for decay into two heavy mesons but above the threshold for decay into heavy bottomonium plus a pion. These can be observed as bottomonium pion or bottomonium kaon resonances in the cascade decays from the higher  $\Upsilon(nS)$  resonances.

The search for intermediate isovector heavy-quarkonium states has been going on for a long time without any positive results. Previous work suggesting possible isovector exotic states as intermediate states in the  $\pi\pi$  cascade decays of heavy quarkonium resonances began with  $\psi' \rightarrow \pi\pi J/\psi$  and was later extended to the  $\Upsilon$  system [2,3]. Unfortunately none of these suggestions were confirmed by later experiments [4–6]. No  $\pi J/\psi$  nor  $\pi\Upsilon$  resonances were found. No theoretical model predicted that tetraquark states would exist close enough to the two-heavy-meson threshold that so they would not be impossibly broad.

New information has recently become available suggesting that these exotic states might now be observable:

1. New data for the  $\Upsilon(5S)$  decays [7] have a serious  $\pi\pi$  problem.
2. A new theoretical model [1] predicts isovector tetraquark states around the  $B\bar{B}$  threshold.

That such tetraquarks should exist for bottomonium and not for charmonium is predicted in this model which has unconventional color couplings and color-space correlations. The two quarks are in a color sextet, the two antiquarks are in a color antisextet, and the color-space correlations require the mean quark-antiquark distance to be considerably smaller than the mean quark-quark and antiquark-antiquark distances.

## II. NEW EXPERIMENTAL DATA SUGGESTING THE EXISTENCE OF TETRAQUARKS

### A. Peculiarities in $\Upsilon(nS)$ production

The Belle Collaboration has recently reported [7] anomalously large partial widths in  $\Upsilon(1S)\pi^+\pi^-$  and  $\Upsilon(2S)\pi^+\pi^-$  production at the  $\Upsilon(5S)$ , more than two orders of magnitude larger than the corresponding partial widths for  $\Upsilon(4S)$ ,  $\Upsilon(3S)$  or  $\Upsilon(2S)$  decays.

We suggest that the large partial widths of these channels might be due to their production by decays via an intermediate  $T_{bb}^\pm\pi^\mp$  state, where  $T_{bb}^\pm$  denotes an isovector charged tetraquark  $\bar{b}b u\bar{d}$  or  $\bar{b}b \bar{u}d$ ,

$$\Upsilon(nS) \rightarrow \pi^\mp T_{bb}^\pm \rightarrow \Upsilon(mS) \pi^-\pi^+ \quad (1)$$

## B. The $Z(4430)$ resonance

In the summer of 2007 Belle reported [8] a narrow resonance-like structure  $Z(4430)$  in the  $\psi'\pi^\pm$  invariant mass with mass and width  $M = 4433 \pm 4(\text{stat}) \pm 2(\text{syst})$  MeV and  $\Gamma = 45^{+18}_{-13}(\text{stat})^{+30}_{-13}(\text{syst})$  MeV. The  $Z(4430)$  has not been seen in the  $J/\psi\pi^\pm$  channel. This report is awaiting confirmation. If it is confirmed, it can be a  $\bar{c}cud\bar{d}$  tetraquark, since it is an isovector and carries hidden charm. Most calculations predict that such states are above the masses of two separated heavy quark mesons as well as  $Q\bar{Q}$  and  $u\bar{d}$  mesons. The  $cu\bar{c}\bar{d}$  and  $bub\bar{d}$  states can therefore decay into states like  $D\bar{D}$  and  $B\bar{B}$  as well as  $J/\psi\pi$  and  $\Upsilon\pi$  with large widths. The narrow width of the  $Z(4430)$  and the lack of the  $J/\psi\pi^\pm$  decay channel are therefore quite puzzling. However a mechanism [9] has been proposed in which the two color eigenstates can be mixed in such a way that the otherwise dominant  $D\bar{D}$  and  $B\bar{B}$  are suppressed. If confirmed, the existence of  $Z(4430)$  would also make it very likely that there is an analogous state in the bottom system.

$Z(4430)$  is approximately 700 MeV above the  $DD$  threshold. But the new Belle data suggest the existence of bottom tetraquarks not far from the  $BB$  threshold, i.e. at much lower mass than the naive bottom analogue of  $Z(4430)$ .

## III. MODELS FOR THE $T^+(bu\bar{b}\bar{d})$ AND $T_S^+(bu\bar{b}\bar{s})$ TETRAQUARKS

Resonant states containing heavy quark  $Q\bar{Q}$  components are expected to decay with large widths into heavy quarkonium  $Q\bar{Q}$  states with one or two additional pions; e.g  $J/\psi\pi$ ,  $J/\psi\pi\pi$ ,  $\Upsilon\pi$ , and  $\Upsilon\pi\pi$  if phase space is available.

One example is the case of the  $Qu\bar{Q}\bar{d}$  tetraquarks whose masses have been shown in a number of cases to be comparable to the masses of two separated heavy-quark mesons [1].

According to [1], the  $bub\bar{d}$  tetraquark can have a mass below the mass of two  $B$  mesons and above the mass of the  $\Upsilon$ . It can decay into  $\pi\Upsilon$ . The  $\Upsilon(2S)$  and  $\Upsilon(3S)$  are both below the  $B\bar{B}$  threshold and could decay into an  $I = 1$  tetraquark and a pion. The  $I = 1$  tetraquark could then decay into the  $\Upsilon(1S)$  and a pion and might decay into an  $\Upsilon(2S)$  and a pion.

The partial widths of  $\Upsilon(5S)$  into  $\Upsilon(nS)\pi^+\pi^-$  are reported [7] to be more than two orders of magnitude larger than the corresponding partial widths for  $\Upsilon(4S)$ ,  $\Upsilon(3S)$  or  $\Upsilon(2S)$  decays. *We suggest looking for the  $\bar{b}bud\bar{d}$  tetraquark in these decays as peaks in the invariant mass of  $\pi\Upsilon(nS)$  systems.*

The  $bub\bar{d}$  configuration was treated in ref. [1] in a harmonic oscillator model with the Nambu interaction. There are two color couplings for a color singlet tetraquark state of two quark antiquark pairs. The two quarks can be coupled to either a color antitriplet or a color sextet, with the two antiquarks coupled to conjugate representations. The triplet-antitriplet tetraquark is denoted by  $\bar{\mathbf{33}}$ , and a sextet-antisextet tetraquark denoted by  $\bar{\mathbf{66}}$ .

The result for the ratio of the ground state energy of the  $bub\bar{u}$  tetraquark to the ground state energy of the separated  $B\bar{B}$  two-meson system was found to be

$$\frac{E_g(\bar{\mathbf{33}}\bar{b}ub\bar{u})}{E_g(2M(\bar{b}u))} = 1.042; \quad \frac{E_g(\bar{\mathbf{66}}\bar{b}ub\bar{u})}{E_g(2M(\bar{b}u))} = 0.891 \quad (2)$$

where  $\bar{\mathbf{33}}$  and  $\bar{\mathbf{66}}$  denote respectively the triplet-antitriplet and sextet-antisextet tetraquark states.

The mass of the  $b\bar{u}\bar{b}\bar{d}$  tetraquark with the color sextet-antisextet coupling is found to be well below the two-meson  $B\bar{B}$  threshold in this approximation. Such a low-mass threshold may also be found in a more exact calculation including spin effects. That they might be found in the experimental spectrum must be taken seriously.

The Belle Collaboration has also reported [7]  $K^+K^-\Upsilon(1S)$  production at the  $\Upsilon(5S)$ . Such states can be produced by decays via an intermediate  $T_s^\pm K^\mp$  state where  $T_s^\pm$  denotes a strange  $\bar{b}bu\bar{s}$  tetraquark

$$\Upsilon(nS) \rightarrow K^\mp T_s^\pm \rightarrow \Upsilon(mS) K^- K^+ \quad (3)$$

*We suggest looking for the  $\bar{b}bu\bar{s}$  tetraquark in these decays as peaks in the invariant mass of  $K\Upsilon(1S)$  or  $K\Upsilon(2S)$  systems.*

The  $b\bar{s}\bar{u}\bar{b}$  tetraquark configuration was not treated in ref. [1]. We apply the same analysis here by simply changing the quark labels and masses, obtaining

$$\frac{E_g(\bar{\mathbf{33}} \bar{b}u\bar{s})}{E_g[(\bar{b}u)(\bar{b}\bar{s})]} = 1.057; \quad \frac{E_g(\bar{\mathbf{66}} \bar{b}u\bar{s})}{E_g[(\bar{b}u)(\bar{b}\bar{s})]} = 0.914 \quad (4)$$

Details of the calculation are given in the Appendix.

The mass of the  $b\bar{u}\bar{b}\bar{s}$  tetraquark with the color sextet-antisextet coupling is found to be well below the two-meson  $B_s\bar{B}$  threshold in this approximation.

## IV. CONCLUSION

Conclusive evidence for the first unambiguous multiquark states would be obtained by finding isovector states or strange states containing heavy quark pairs. Model calculations suggest that such states should exist with masses below the  $B\bar{B}$  threshold but above the  $\pi\Upsilon(nS)$  or  $K\Upsilon(nS)$  thresholds. Searches are suggested for these states by measuring the invariant masses of  $\Upsilon(nS)\pi$  and  $\Upsilon(nS)K$  pairs produced in the cascade decays of a higher  $\Upsilon(nS)$  resonance to lower  $\Upsilon(nS)$  states by pion pair or kaon pair emission. Such transitions are suggested by present data indicating anomalous production of  $\Upsilon(nS)\pi\pi$  states in  $\Upsilon(5S)$  decays.

## APPENDIX

The ground state energies of the  $b\bar{s}\bar{u}\bar{b}$  states are given by the sum of the ground state energies of the contributing harmonic oscillators. The ground state energy of an oscillator with co-ordinate  $r$ , mass  $M$  and potential  $Vr^2$  is

$$E_g(osc) = \frac{3}{2} \cdot \hbar\omega = \frac{3}{2} \cdot \hbar\sqrt{\frac{V}{M}} \quad (5)$$

For the two-meson  $(\bar{b}u; b\bar{s})$  system, which has two separated harmonic oscillators with reduced masses denoted by  $M(bu)$  and  $M(bs)$  and potentials  $V_o/2$  from ref. [1],

$$E_g[(\bar{b}u)(b\bar{s})] = \frac{3}{2} \cdot \hbar \left( \sqrt{\frac{V_o}{2M(bu)}} + \sqrt{\frac{V_o}{2M(bs)}} \right) \quad (6)$$

The ground state energies for the  $\bar{\mathbf{33}}$  and  $\bar{\mathbf{66}}$  systems are obtained by substituting the potentials from ref. [1] into the expression (5) along with the reduced masses

$$M(bs) = \frac{m_b m_s}{m_b + m_s}; \quad M(bu) = \frac{m_b m_u}{m_b + m_u}; \quad M\{(bs)(bu)\} = \frac{(m_b + m_s) \cdot (m_b + m_u)}{m_b + m_s + m_b + m_u} \quad (7)$$

$$E_g(\bar{\mathbf{33}}) = \frac{3}{2} \cdot \hbar \left( \sqrt{\frac{V_o}{2M\{(bs)(bu)\}}} + \sqrt{\frac{3V_o}{8M(bs)}} + \sqrt{\frac{3V_o}{8M(bu)}} \right) \quad (8)$$

$$E_g(\bar{\mathbf{66}}) = \frac{3}{2} \cdot \hbar \left( \sqrt{\frac{5V_o}{4M\{(us)(bu)\}}} + \sqrt{\frac{3V_o}{16M(bs)}} + \sqrt{\frac{3V_o}{16M(bu)}} \right) \quad (9)$$

The ratios of these energies to the energy of the two meson state are then

$$\begin{aligned} \frac{E_g(\bar{\mathbf{33}} \bar{b}ub\bar{s})}{E_g[(\bar{b}u)(b\bar{s})]} = \\ \sqrt{\frac{3}{4}} + \frac{\sqrt{(m_b + m_s + m_b + m_u)m_s m_b m_u}}{m_b(m_u - m_s)} \cdot \left[ \sqrt{\frac{m_u}{m_b + m_u}} - \sqrt{\frac{m_s}{m_b + m_s}} \right] = 1.057 \end{aligned} \quad (10)$$

$$\begin{aligned} \frac{E_g(\bar{\mathbf{66}} \bar{b}ub\bar{s})}{E_g[(\bar{b}u)(b\bar{s})]} = \\ = \sqrt{\frac{3}{8}} + \sqrt{\frac{5}{2}} \cdot \frac{\sqrt{(m_b + m_s + m_b + m_u)m_s m_b m_u}}{m_b(m_u - m_s)} \cdot \left[ \sqrt{\frac{m_u}{m_b + m_u}} - \sqrt{\frac{m_s}{m_b + m_s}} \right] = 0.914 \end{aligned} \quad (11)$$

where we have substituted the values of the constituent quark masses obtained by fitting the ground state meson and baryon spectra [10].

$$m_b = 360 \text{ MeV}; \quad m_s = 540 \text{ MeV}; \quad m_u = 1710 \text{ MeV}; \quad m_b = 5050 \text{ MeV} \quad (12)$$

## ACKNOWLEDGEMENTS

The research of M.K. was supported in part by a grant from the Israel Science Foundation administered by the Israel Academy of Sciences and Humanities. We thank Bill Dunwoodie, Inga Karliner, Steve Olesen, Jon Thaler and Misha Voloshin for useful discussions.

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